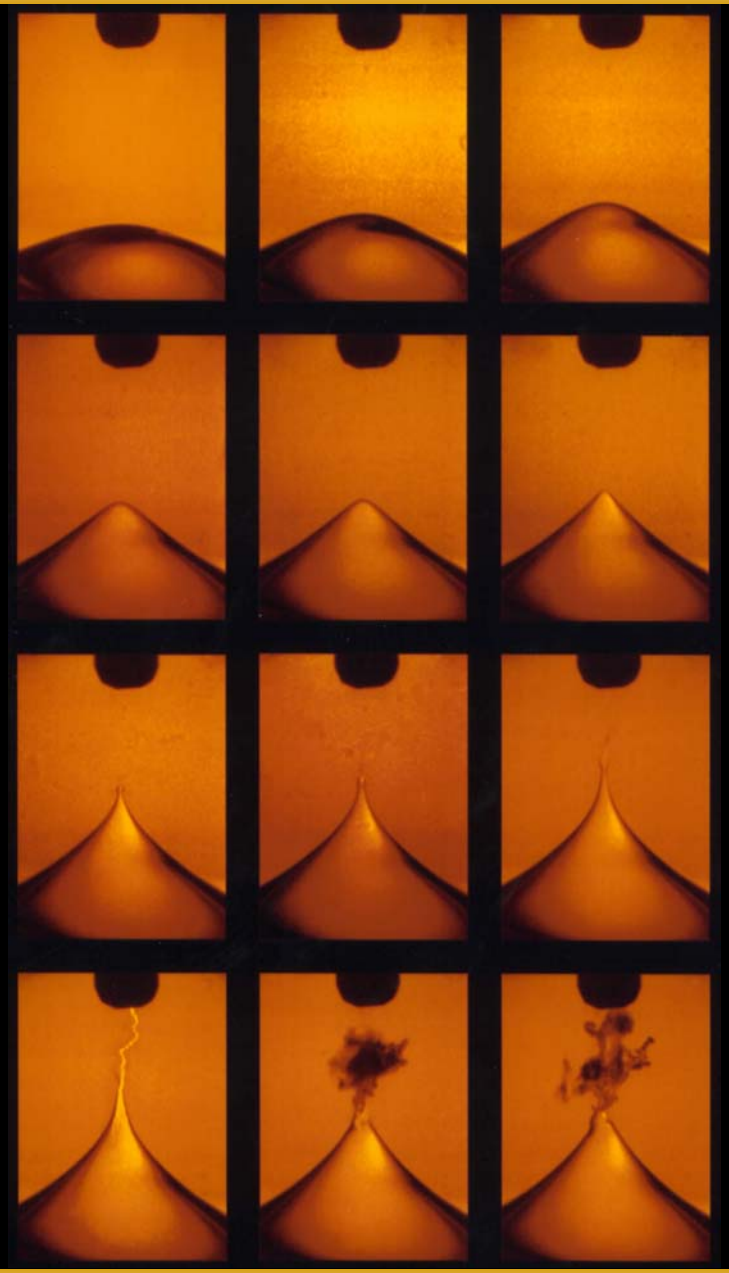
Electro-Hydrodynamic Spouts in Conducting Liquids



A Storm in the Laboratory: Formation of charged jets ("lightning") that break up into liquid droplets ("rain")

Lene Oddershede and Sidney R. Nagel, *Phys. Rev. Lett.* **85**, 1234-1237 (2000);

Series of 12 high-speed photographs showing the evolution of a sharply pointed “spout” at the interface between an upper layer of non-conducting fluid (lighter color) and a lower layer of conducting fluid (darker color), subjected to a strong electric field (produced by dark round electrode at top of each image).

A Storm in the Laboratory: Electro-Hydrodynamic Spouts

The spout formation showcases key features of non-linear systems:

- surprising changes of behavior (here: from “lightning” to “rain”), and
- novel structures (here: the corkscrew instability of the jet).

A better understanding of such non-linear systems has been brought to a broad public through such activities as our Center’s partnership with the nearby Museum of Science and Industry, our recent museum conference, and our publications in journals aimed at a broader public, e.g. Critical Inquiry, Perspectives in Biology and Medicine and in broad impact scientific journals, e.g., Nature, Science, and Physics Today.

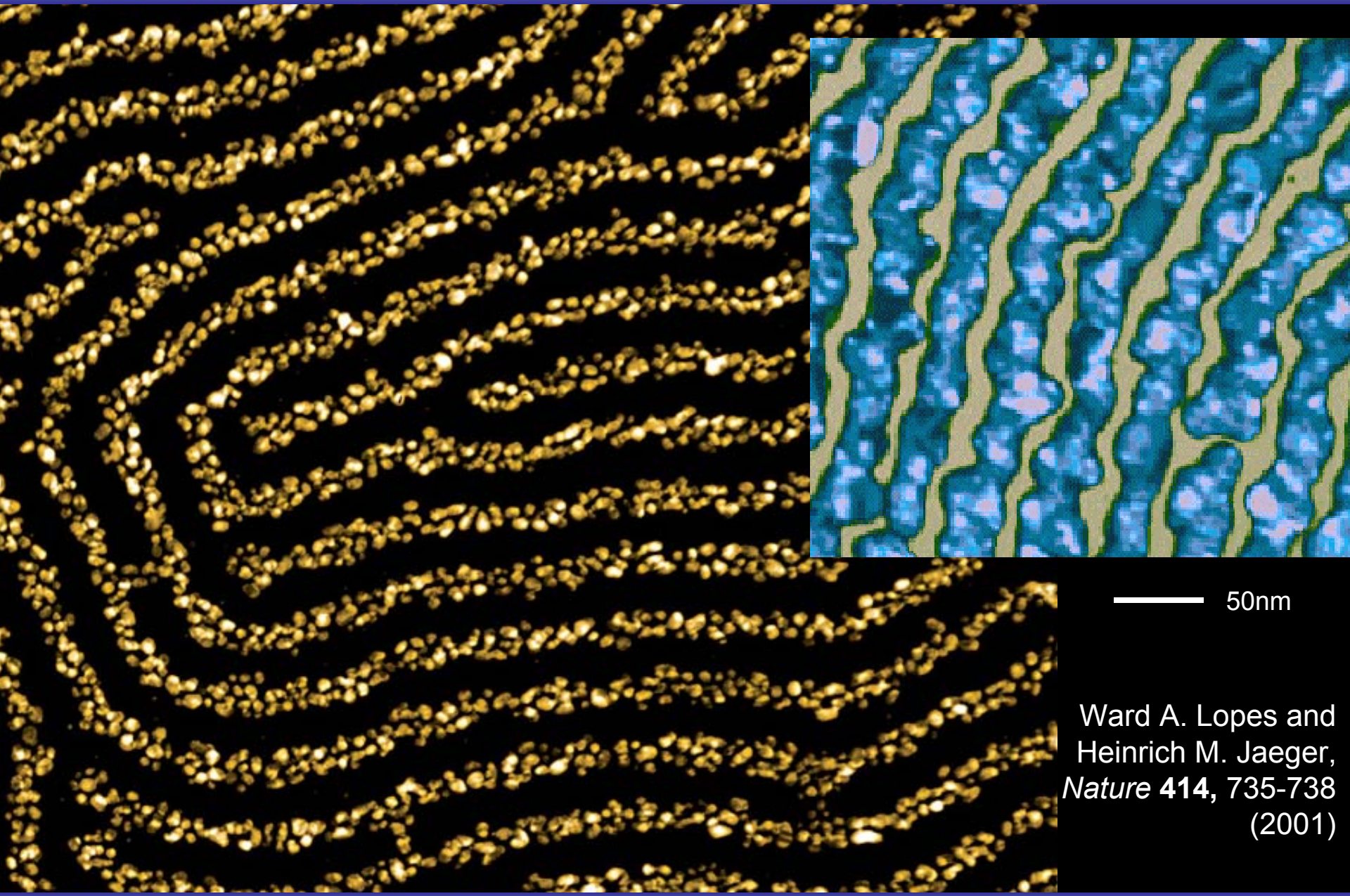
This work has been useful for the development of young scientists. Examples:

Wendy Zhang, with a background chemical engineering, applied sciences, and physics who went from an NSF postdoc to an assistant professorship in in our physics department.

Lene Odderhede, who went from being a graduate student visitor in our MRSEC to being the leader of a group of young women faculty in Copenhagen investigating problems in biological physics.

Moses Hohman, who went from being a graduate student in our materials laboratory to being the leader of the Indian office of a US business software firm.

Nanochains & Nanowires on Diblock Copolymer Scaffolds



Ward A. Lopes and Heinrich M. Jaeger, *Nature* **414,** 735-738 (2001)

Explanation

Main image: Transmission electron micrograph of gold nanoparticle chains (yellow) on a PS-PMMA diblock copolymer template, zooming
in on one of the patterns to show the individual nanoparticles.

Small image: Silver nanowires (blue-grey) on the same type of template.

Both images: The center-to-center spacing between adjacent chains or wires is 50 nm.

Two important, yet competing issues in the assembly of inorganic materials on block copolymeric scaffolds are high metal density vs. domain selectivity. While selective aggregation of the metal along one domain of a copolymer thin film occurs because of preferential wetting of one of the copolymer blocks, metal-metal bonding often completely overwhelms metal-polymer bonding at higher metal concentrations due to the large surface energies of metals (exceeding those of copolymers by orders of magnitudes).

In this example, the asymmetric diblock copolymer, polystyrene-block-poly(methyl-methacrylate) (abbreviated PS-PMMA) after annealing, produces a thin film consisting of laterally alternating domains. When a small amount of metal is thermally evaporated onto the copolymer film, selective decoration of one of the two copolymer domains is immediately apparent. We found this to be a general method for assembling metal nanostructures: gold and silver appear to prefer the PS domain, while indium, lead, tin, and bismuth prefer the PMMA domain.

When one attempts to use large concentrations of gold, and other metals (with the exception of silver), however, the metal eventually ignores the template, "jumping the gap" between neighboring domains. Because subsequent annealing fails to restore selectivity, this indicates that the selective aggregation of the metal particles does not represent an equilibrium state, but is, rather, a dynamic effect. Therefore, one technique, that of repeated deposition and short-time annealing of small amounts of metal (equivalent to generating a large number of nucleation sites for metal droplet formation in the preferred domain) was specifically developed to take advantage of this observation. This results in dense metal nanochains (essentially 100% selectivity; >40% metal loading by volume inside the PS domain), as illustrated in the main figure.

Silver metal, in contrast to all the other metals investigated, easily forms continuous nanowires along the PS domains. No annealing is required to produce silver nanowires following the 25nm wide polymer scaffolds over distances of micrometers without breaks.

Practically, both the self-assembled nanochains and nanowires were found completely suitable for electronic transport. The nanochains exhibited highly non-linear current-voltage curves, characteristic of single-electron tunnelling between nanometer-sized metal islands in the presence of strong charging effects. At low voltage bias, the structures are essentially insulating but switch over to conducting behavior beyond the threshold. By contrast, the I-V curves for the nanowires are linear, indicative of continous, metallic connections across the sample.

- Research primarily performed by underrepresented ethnic minority grad student, now working in as Head Scientist at a high-tech start-up; predict a long and fruitful career at the forefront of technology.
- Project demonstrates elegant and effective strategy using **guided self-assembly**, with broad applicability for the creation of novel nanostructured materials.
- Work published in high-profile and widely disseminated journal (*Nature*).
- Outcome enabled by an interdisciplinary team approach involving chemists and physicists, experiment and supporting theory/simulation, and including full participation by researchers from the undergrad level on up.